The Causes of Geomagnetic Storms During Solar Maximum

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I. SOLAR PHENOMENA

One of the oldest mysteries in geomagnetism is the linkage between solar and geomagnetic activity. Sabine (1 852), first noted that both the numbers of sunspots and geomagnetic storms at Earth have an eleven year cycle. A few years later, Barrington (1 860) reported that a large magnetic storm followed the great September 1859 solar flare and a causal relationship between flares and storms was speculated. It was not until this century that a well-accepted statistical survey on large solar flares and geomagnetic storms was performed (Newton, 1943). The results indicated that a significant correlation between flares and geomagnetic storms exist.

Although the two phenomena, one at the Sun and the other at the Earth, were statistically correlated, the exact physical linkage was still an unknown at this time. Various hypotheses Were proposed . It was not until interplanetary spacecraft measurements were available that a high sped plasma stream was associated with an intense solar flare (Hirshberg et al., 1970). The high speed stream was rich in helium. The velocity of the solar wind increased just prior to and during the helium passage, indicating the auroral ejecta was identified for the first time. Space plasma measurements and the Skylab's coronagraph images of mass ejections from the Sun firmly established the plasma link between the Sun and the Earth.

Figure 1, is an example of a coronal image of a solar ejection, called a Coronal Mass Ejection, or CME (Gosling et al., 1975). Although it was originally thought that the magnetic annihilation (which is the cause of solar flares) provided the energy for the expulsion of the coronal material, careful timing analyses demonstrated that the CMEs are released first, and thus flares arc after-effects of the mass ejections (Harrison, 1986). "This has led to some severe rethinking of how mass is ejected from the solar corona.

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11. TYPES OF SOLAR WIND

'J'here have been plasma and magnetic field instruments onboard interplanetary spacecraft since the early 1960s. These experiments discovered that there is a continuous flow of plasma coming outward from the Sun. At 1 Astronomical Unit (the Earth's distance from the Sun), this "solar wind" has a nominal velocity of - 400 km s-1 and a density of -4 to 10 particles cm^{-3}. The plasma consists of primarily hot electrons ('J'$_c$- 1.5 x 10^5 K) and protons ('J'$_p$-- ().8x 10^4 K) with a minor fraction ($\sim$ 3-5%) of He^{++} ions. The plasma has an embedded magnetic field of intensity -5 nT. At Earth, 1 AU from the Sun, the typical thermal plasma to magnetic field energy density ratio, beta (8πnkT/B^2), is roughly 1.0. in the equation n is the plasma density, k the Boltzmann constant and B the magnetic field intensity.

Besides the quiescent solar wind discussed above, at times near solar maximum (by definition when there is a maximum number of sunspots), high speed streams occur with velocities occasional] y greater than 600" km s-1 and sometimes even greater than 1,000 km s-1. If we use Newton's 1943 statistics, we now know that approximately 90% of these high sped streams at solar maximum are associated with CM] :s. Because the ambient magnetosonic wave speed is only $\sim$ 1 ()() km s^{-1}, the difference in flow velocity between the faster stream and the slower stream is greater than the magnetosonic (fast mode) speed. 'J 'bus, a fast forward shod is formed at the leading edge of the high-sped stream.

A schematic of the shock and driver gas is shown in Figure 2. The shock is the outermost (antisunward) extension of the solar disturbance's propagation into interplanetary space. The region immediately behind (sunward of) the shock is composed of swept-up, compressed and accelerated plasma and fields from the "slow" stream and is called the "sheath" region. Behind this is the driver gas (CME) proper. The driver gas has previousl y been identified by a variety of signatures: enhanced 1 Ielium/hydrogen density ratios, low ion temperatures, high intensity magnetic fields with low variances and bi-directional streaming of thermal ions and electrons. It should be mentioned that no one measurement or combination of measurements have proved to be a perfect means of identification, however (Zwickl et al., 1983; Choe et al., 1992). Intense research in this area is still ongoing.

Because of the typically high intensity magnetic fields (10-50 nT) and low plasma temperatures, the driver gas is a low beta plasma, β = ().()3 - ().8 (Choe et al. 1992). in about 1 0% of the cases, the magnetic field in these regions has an unusual configuration, with large out-of-the ecliptic components. This has been named a magnetic cloud (Klein and Burlaga, 1982). A recent schematic of the magnetic field configuration is shown in Figure 3 (Marubashi, 1986).

When crossing the cloud, the field rotates from north-to-south or south-to north with a lime scale of a day or longer. This configuration is believed to be force-free, supported only by field-aligned currents flowing inside of it.

One fundamental question concerning this magnetic field region is whether it is "closed" like a magnetic bubble, or whether it is a loop with both ends remaining attached to the Sun. The presence of bi-directional streaming electrons and protons in this region have been used to argue for a closed magnetic structure (Gosling et al. 1987). However, the observations of energetic solar flare particles both outside and inside of this structure and the small amount of modulation of cosmic rays by these structures, have been used to argue for an open structure still connected back to the Sun (Kahler and Reames, 1991). The argument about open or closed structures persist because one-spacecraft "cuts" through the three-dimensional structure cannot resolve such a question. Mulii-spacecraft measurements are needed.

III. MAGNETIC RECONNECTION AND MAGNETIC STORMS

The high speed plasma events which are led by shocks, followed by plasma sheaths and then the driver gases, do not have direct access to the Earth's dayside atmosphere and ionosphere. The protective magnetosphere which is created by the internal magnetic field of the Earth, deflects the interplanetary plasma and fields, so the latter flow around the magnetosphere. The solar wind plasma primarily enters the magnetosphere through magnetic connection between the interplanetary magnetic fields and the Earth's outer fields, as schematically shown in Figure 4. When the interplanetary magnetic field (1 MF) has a component with a direction opposite (southward to the magnetospheric fields (northward), interconnection can take place, and the solar wind convects these fields back into the tail region where they reconnect once more (Dungey, 1961; Vasyliunas, 1975). The magnetic tension on the freshly reconnected tail fields "snaps" the reconnected fields and plasma forward toward the nightside of the Earth. The convection process, through conservation of the first two adiabatic invariant (p and$_4$ p^{ds}), energizes the plasma. When the magnetic dayside connection is particularly intense, the nightside reconnection is also correspondingly high, and the plasma is driven deep into the nightside inner magnetosphere. Because the plasma is anisotropically heated by this process, plasma instabilities (Ioss-cone instabilities) occur, creating electromagnetic and electrostatic plasma waves, which cyclotron resonate with the energetic particles (Kennel and Petschek, 1966). The wave-par[ic]c interactions break the particles' first adiabatic invariant, scattering them in pitch angle. l'articles that have their mirror points lowered to altitudes at

atmosphere/ionosphere heights are lost by collisions with atmospheric/ionospheric particles. in the loss process, atmospheric/ionospheric atoms and molecules are excited, resulting in characteristic aurora] emissions. The above scenario is the cause of the diffuse aurora, a phenomenon which occurs primarily in the Earth's midnight sector. The spreading of the aurora toward local dawn is caused by electron azimuthal drift, a topic that will be discussed shortly.

The nightside convection electric field which drives the plasma from the tail into the nightside inner magnetosphere has a dawn-to-dusk orientation. When this field develops discontinuities with $\mathbf{V} \cdot \mathbf{E} < 0$, magnetically field-aligned currents with associated field-aligned electric potential differences and electron precipit at i on develop. This powers the -- 1()() km scale aurora] precipitation (1 .yons, 1980; 1992). Aurora of this type. arc shown in Figure 5.

As the energetic particles are convected deep into the Earth's nightside magnetosphere, they are also subjected to forces due to the magnetic field curvature and gradient as well as forces due to particle gyration effects. For the same charge sign, these forces act in unison, and the net effect is that protons drift from midnight toward dusk and electrons from midnight toward dawn (1 igure 6). This oppositel y directed drift comprises a ring of current (the ring current) around the Earth. The current is a diamagnetic one, decreasing the intensity of the Earth's field. An enhanced ring current is the prime indicator of a magnetic storm. The total energy of the, particles in the ring current (measured by the intensity of the diamagnetic field perturbation), is a measure of the storm intensity (Dessler and Parker, 1959).

We now compare the interplanetary features discussed previously and their relationships to the phases of a magnetic storm, shown in 1 igure 7. in the Figure, the ordinate gives the change in the horizontal component of the Earth's magnetic field, measured by a chain of ground based stations located near the equator (the ordinate is the field averaged over these stations). The abscissa gives time. 'J'here arc three phases to a geomagnetic storm, as indicated in the Figure. They arc called the initial phase, where the horizontal component increases to positive values of up to 1 O's of nT, a main phase which can have magnitudes of negative hundreds of nT, and a recovery phase where the field graduall y returns back to the am bient level. An average of these deviations from the field ambient value is called the D_{ST} index, measured in nT. The time scales of the three phases arc variable. The initial phase can last minutes to many hours, the main phase a half-hour to several hours, and the recovery from tens of hours to a week,

The initial phase is caused by the solar wind ram pressure ($1/2 \rho V_{SW}^2$) increase as the interplanetary shock wave hits the front side m agnetosphere. There arc both abrupt velocity and plasma density increases across the shock that lead to the dramatic ram pressure increase. This

pressure pulse rapidl y compresses the magnetosphere anti causes the increase in the average field at the equator.

The storm main phase. onset is initiated by a southward IMF and consequential enhanced magnetic reconnection. Due to enhanced nightside convection, the Van Allen radiation belt particles increase in number and average energy. As the ring current increases, the diamagnetic current causes the decrease in the Earth's field.

The third, or recovery, phase of the storm is due to the decay of this belt of energetic particles. "1'here arc four fundamental mechanisms for this 10ss:]) wave-parliclc interactions, where waves pilch-angle scatter the particles into the "loss cone", 2.) for charged particles wi th low mirror points or those trapped on field lines within the plasmasphere (a region of high density plasma), Coulomb interactions take place, 3) charge exchange with neutrals is a dominant loss mechanism, particularly at large 1., (the 1. value of a magnetic field line is the distance in Earth radii from the Earth's center to the equatorial plane crossing of the field), and 4) convection across the dayside magnetopause will lead to loss within the magnetosheath. The first three processes occur within the storm main and recovery phase. 'J he fourth mechanism only occurs during the main phase. During particularly intense storm main phases where the 10ss time scales can be as rapid as an hour or less, the most probable mechanism is wave-par[iclc interactions. This has not been observationally confirmed, however.

One type of aurora, which is specifically associated with magnetic storms, is the brilliant "blood" red aurora shown in Figure 8. The red aurora is created by the emission of a 6300 $\overset{\circ}{A}$ oxygen line and occurs at very high altitudes (200-600 km) where the collisional de-excitation time scales arc larger than the metastable decay time of - 200 s. One thought (Cornwall et al., 1971) is that electromagnetic ion cyclotron waves generated by the 10ss cone instability of the ring current protons get damped and accelerate the magnetospheric thermal electrons up to energies of 2-3 cV. These low energy electrons arc stopped high in the atmosphere resulting in the aurora. Another possibility (Fok et al., 1991) is that ring current ions and electrons arc scattered and slowed down by Coulomb interactions with thermal plasma and arc eventually removed from trapped orbits. "J'here is now more evidence pointing toward the latter mechanism.

IV. AN INTERPLANETARY EXAMPLE

Previously, in Figure 2, wc showed the profile of the two primary regions where intense southward interplanetary magnetic fields can occur within the high-speed streams: in the sheath region behind the shock, and in the driver gas. Wc showed that a flux-rope configuration could

lead to large southward (and northward) field orientations, magnetic connection at the Earth's magnetosphere (when the IMF is southward), and aurora, Figure 9 illustrates five. observed and hypothesized mechanisms for sheath southward fields. Preexisting southward fields can simply be (a) compressed by the shock, (b) the heliospheric current sheet which separates the northern and southern heliospheric fields can be distorted and compressed by shock compression, and (c) large amplitude waves and turbulence or the presence of discontinuities can be associated with o~lt-of-tl~c-ecliptic field components, (d) the sheath plasma flows around the driver gas, the magnetic fields will drape over it, much like the field draping around a comet. The magnetic tension will expel plasma down the lines of force creating a low beta region near the stagnation region (Zwan and Wolf, 1976). A mechanism has been demonstrated for creating large scale north-south fields from flows around an object like a driver gas (c). The illustration gives an example of this. Finally, because the Earth's dipole is substantially tilted in the y-z plane during the equinoxes (see f), fields in the ecliptic plane (y axis) will have B_z components in the solar magnetospheric (SM) coordinate system, the coordinate system relevant for magnetic reconnection.

It should be noted that in the two regions, the sheath and the driver gas, the field orientation has been found empirically to be northward-directed with equal probability as for southward orientations (Gonzalez and Tsurutani, 1987). There are also cam where the field lies primarily in the ecliptic as well as cases with large north-south components which vary rapidly in time. The latter cases do not cause storms because of their short reconnection/convection time scales. The result is that only one in about 6 cases of CMEs that impinge upon the Earth lead to an intense $(D_{ST} < -100$ nT) magnetic storm (Tsurutani and Gonzalez, 1990). *Note* that the above mentioned driver gas fields apply to storms which occur at m" near solar maximum. Less is known about possible equivalent structures during solar minimum.

Many of the solar win(i-magnetic storm relationships discussed above can be illustrated by showing some space plasma data. An example is given in Figure 10. From top to bottom, the panels give the solar wind velocity, plasma density, magnetic field magnitude, two components of the magnetic field in GSE coordinates, the Auroral Electrojet index (AE) and D_{ST} in the GSE coordinate system, x-points toward the Sun, y is in the ecliptic plane pointing in the direction of rotation of the planets, and z completes the right-hand system. The auroral electrojet is an ionosphere current which flows al - 1()() km altitude and is typically located at auroral latitudes (- 63-68° magnetic latitude). The location moves equatorward during magnetic storms. This current becomes particularly intense during active am-oral displays and can math amplitudes

of up to 10^7 Amperes. The AE index is a ground-based measurement of the magnetic field associated with this current.

An interplanetary shock is noted in the Figure at the beginning of August 27 by an abrupt jump in the solar wind velocity, density and magnetic field magnitude. The increase in ram pressure leads to an increase in D_{ST} to positive values. This is the onset of the storm initial phase. Towards the end of the day, B_z turns negative (southward) and remains in this direction for over 12 hours. D_{ST} decreases in response, signifying the start of the storm main phase, i.e., the ring current build-up. As the IMF B_z turns positive (northward), D_{ST} begins to increase and the onset of the recovery phase begins.

For the interval of August 1978 - December 1979 anti using the ISEE-3 observations, Gonzalez and Tsurutani (1 987) found that the ten intense storms ($D_{ST} < -100$ nT) that had occurred in this time interval were associated with large-intemily (< -10 nT) and long-duration (> 3 hours) negative B_z events, of the type of that shown on Figure 10.

in the storm event of Figure 10, the recovery phase is exceptionally long. Continuous auroral activity (AE) is associated with this interval and is illustrated by the bar in the AE pane]. During this lime, the interplanetary medium is characterized by rapid fluctuations in the transverse (y and z) components of the magnetic field. The field magnitude is relatively constant. Analyses of the field and plasma data indicate that these fluctuations are Alfvén waves (Belcher and Davis, 1971) propagating outward from the sun. Use of magnetic field measurements on spacecraft closer to the Earth have demonstrated that the AE increases are correlated with southward deviations of the field, the latter associated with the Alfvén waves. "1'bus, the auroral (AE) activity is due to magnetic reconnection (Tsurutani et al., 1990). However, it is noted that there is very little ring current activity (D_{ST}) during this extended interval.

The lack of ring current activity can be understood by the nature of the southward field components Of the Alfvén waves. The fields are less intense than those during the storm main phase (see Figure) and their durations are considerably shorter. Thus the consequential nightside convection will be of lower velocity and will occur sporadically. Plasma will only be brought into the outer regions of the magnetosphere where they feed the high latitude aurora and not deep into the magnetosphere where the ring current predominantly resides.

Other types of solar wind-magnetospheric interactions had been hypothesized, such as a "viscous interaction" between the solar wind and the magnetosphere (Axford and 1 lines, 196 I). '1'here is evidence that the Kelvin Helmholz instability occurs when the IMF is orthogonal (northward to the tail field direction. 1 lowever, it was recently shown that only -0.1 % of the

solar wind ram energy enters the magnetosphere during these events, as compared to 10% during magnetic reconnection intervals (storm events) (Tsurutani et al., 1992).

Another "viscous type" of interaction is resonant wave-particle interactions near the dayside magnetopause. It has been shown that electromagnetic and electrostatic waves can scatter magnetosheath plasma across this boundary at a rate which approaches 10% of the Bohm diffusion rate (Tsurutani and Thorne, 1982). The diffusion and pitch angle scattering have been speculated to be the cause of the dayside aurora, a low-level feature which is almost always present.

V. FUTURE SPACE PHYSICS MISSIONS

Where do we go from here? How are we going to fully understand the flow of energy from the sun to the magnetosphere and the eventual sinks in the ionosphere and magnetotail? One future space mission is the international Solar Terrestrial Physics (1 S'1'1') mission which is devoted to quantitatively solve the energy flow problem discussed in this paper. The National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Russian Space Research Institute (IKI) and Japanese Institute of Space and Astronautical Science (ISAS) scientists will place spacecraft in interplanetary space. (WIND, SOHO and Cluster), in the magnetosphere (Polar, and Cluster) and in the tail (GEOTAIL) to do this energy mapping.

Lastly, a mission of the future is the Small Solar Probe spacecraft. This mission is being considered as another joint NASA/ESA/IKI/ISAS mission. The Small Solar Probe is designed to go to a distance as close as 4 solar radii from the sun's center. The beat shield will reach -2100 K at 4 1<s, a temperature that will melt most metals or at least make them limp or brittle. Small Solar Probe will use carbon-carbon for the shield. 11 will protect the scientific instruments which arc located in the shield's umbra, and will allow them to operate at a temperature of -20" C. The international complement of instruments will measure in situ fields and particles to establish the cause(s) of coronal heating and the acceleration of the solar wind, determine the characteristics of microflares and possibly even detect the release of a CME. This mission will probe one of the two remaining frontiers of our heliosphere.

ACKNOWLEDGMENTS

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Figure Captions

Fig. 1. The March 18, 1989 coronal mass ejection. Courtesy of A. 1 lundhausen.

Fig. 2. A schematic of a plasma driver gas, sheath and shock. Propagation is to the right. At the core of the driver gas is a low β region characterized by low field variances, low plasma temperatures and 1 lelium enhancements. '1'here is sometimes a Helium shell around this low beta region. The shape of the driver has been determined by magnetic field normal analyses. nom Choe et al. (1992).

Fig. 3. A possible configuration of the magnetic fields within the low beta portion of the driver gas. Taken from Marubashi (1986).

Fig. 4. Magnetic reconnection between interplanetary and magnetospheric magnetic fields. Taken from Gonzalez and Tsurutani, 1992.

Fig. 5. An example of the aurora borealis. Taken in Fairbanks, Alaska by S.-1. Akasofu.

Fig. 6. Energetic particle motions: gyro, bounce and drift. Taken from Williams (1985). 1)erived from W. 1 Icss and L. J. Lanzerotti.

Fig. 7. The three phases of a magnetic storm. See discussion in Gonzalez et al. (1992).

Fig. 8. A red aurora. These aurora can occur at low latitudes and are associated with magnetic storms. Courtesy of Vic Hessler of the Geophysical Institute, University of Alaska, 1 airbanks, AK.

Fig. 9. The various proposed causes of southward magnetic fields in the sheaths of high-speed interplanetary streams.

Fig. 10. An example of a solar flare-related high speed interplanetary stream and its geomagnetic effects. Taken from Tsurutani et al. (1988).

DATE
89: 077

TIME
83:34:58

18 MAR
1989

FILTER
GREEN

POLAROID
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SECTOR
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EXPOSURE
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RESOLUTION
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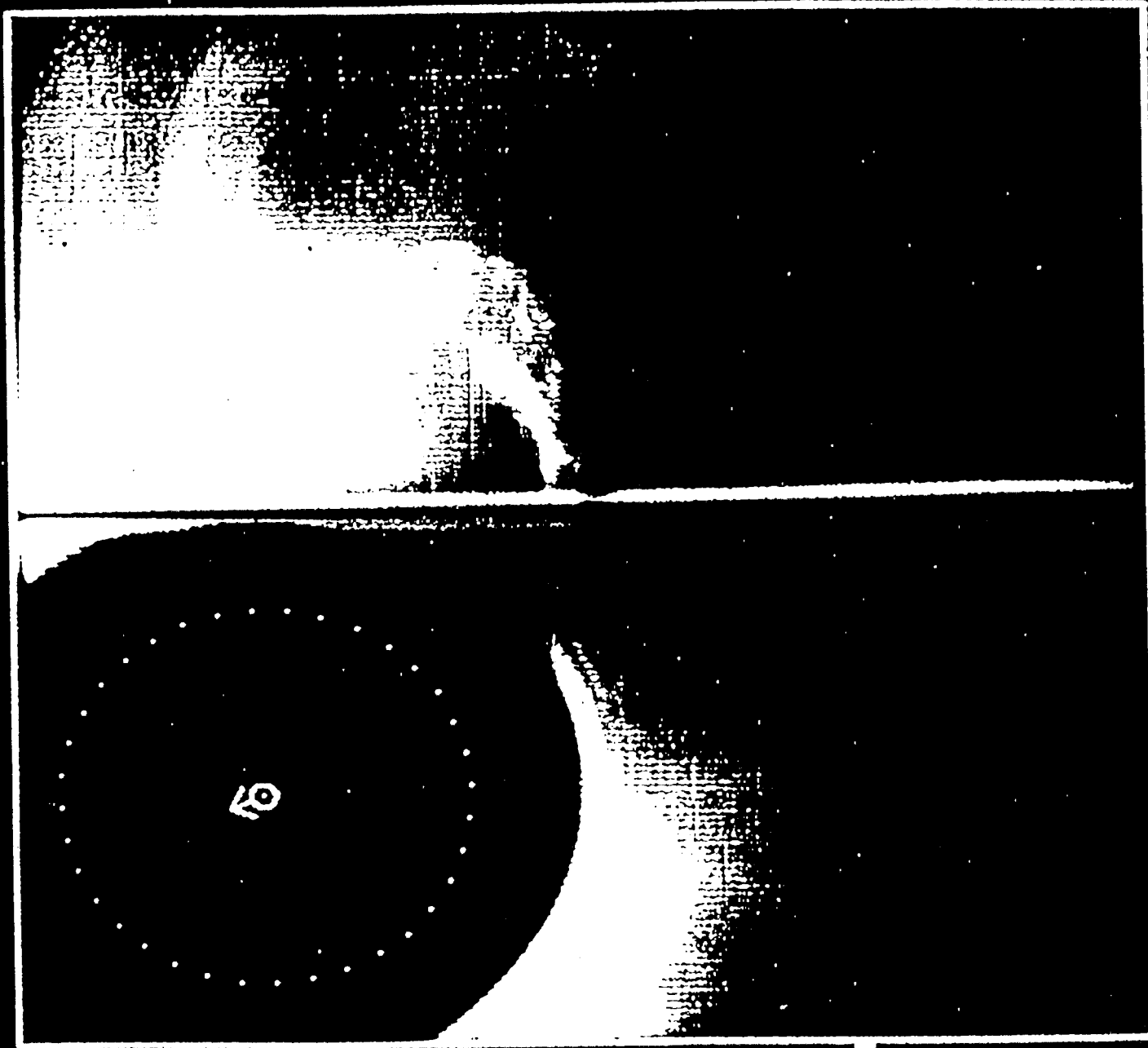
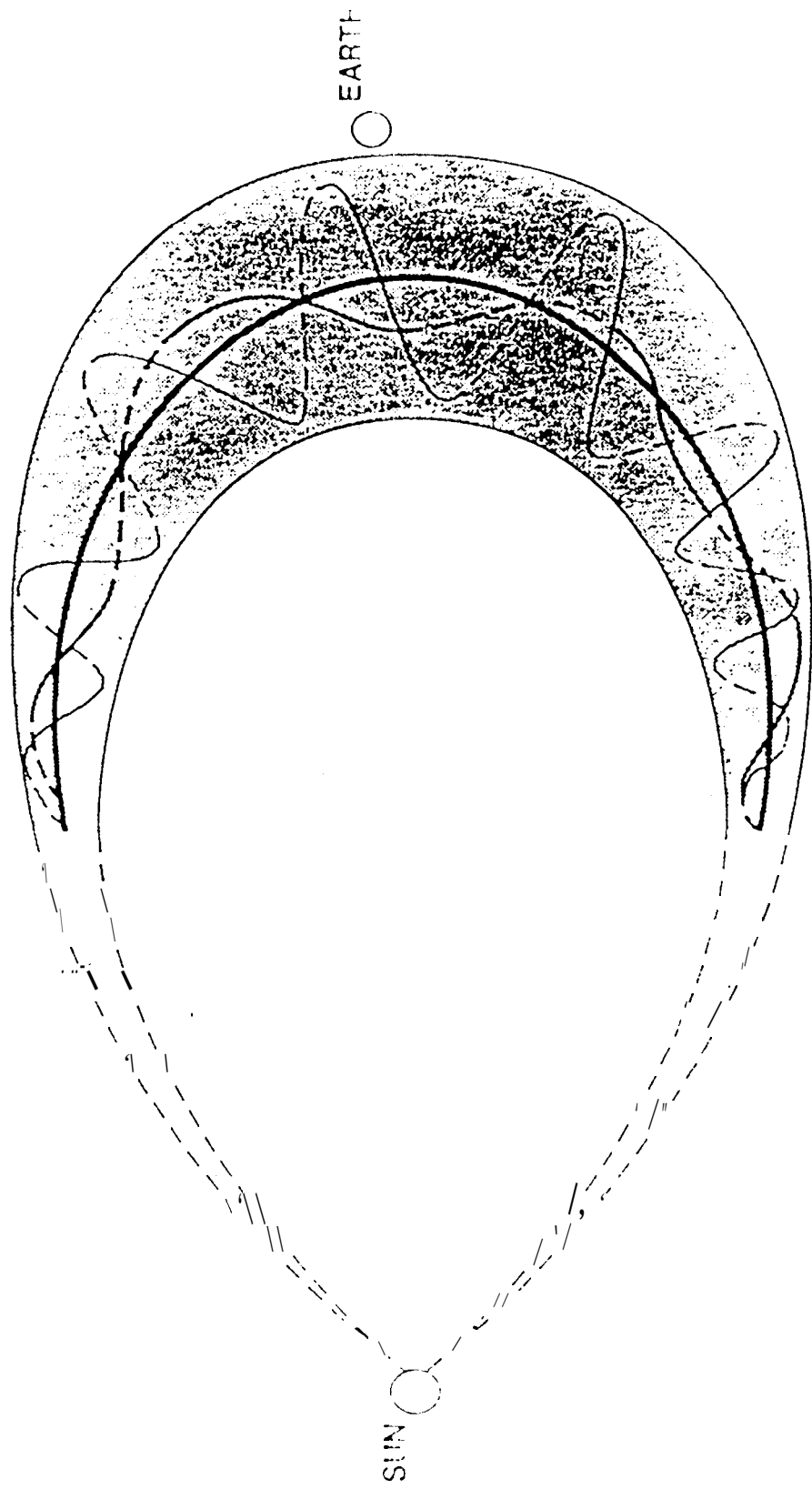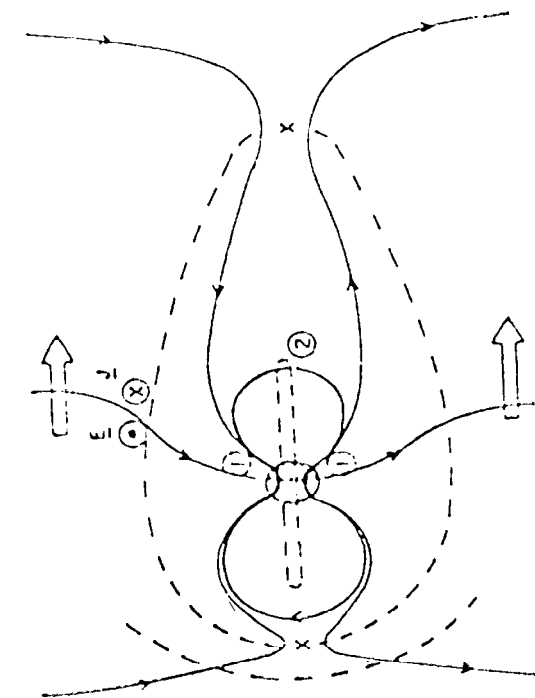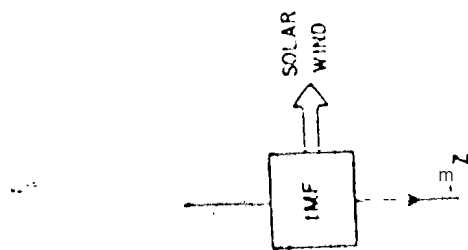HAO/SMM   CORONAGRAPH / POLARIMETER

V_SW

He/H increase
high temperature
high |B|

shock

sheath

D1

B1

"raisins"
He/H enrichments

BDE, BDP
low B variance
high |B|
low temperature

B2

D2

? ? ?

inner boundary

outer boundary

Fig. 2

EARTH

SUN

Fig. 3

EARTH'S MAGNETOSPHERE

SOLAR WIND

IMF →m_z

SUN
CME
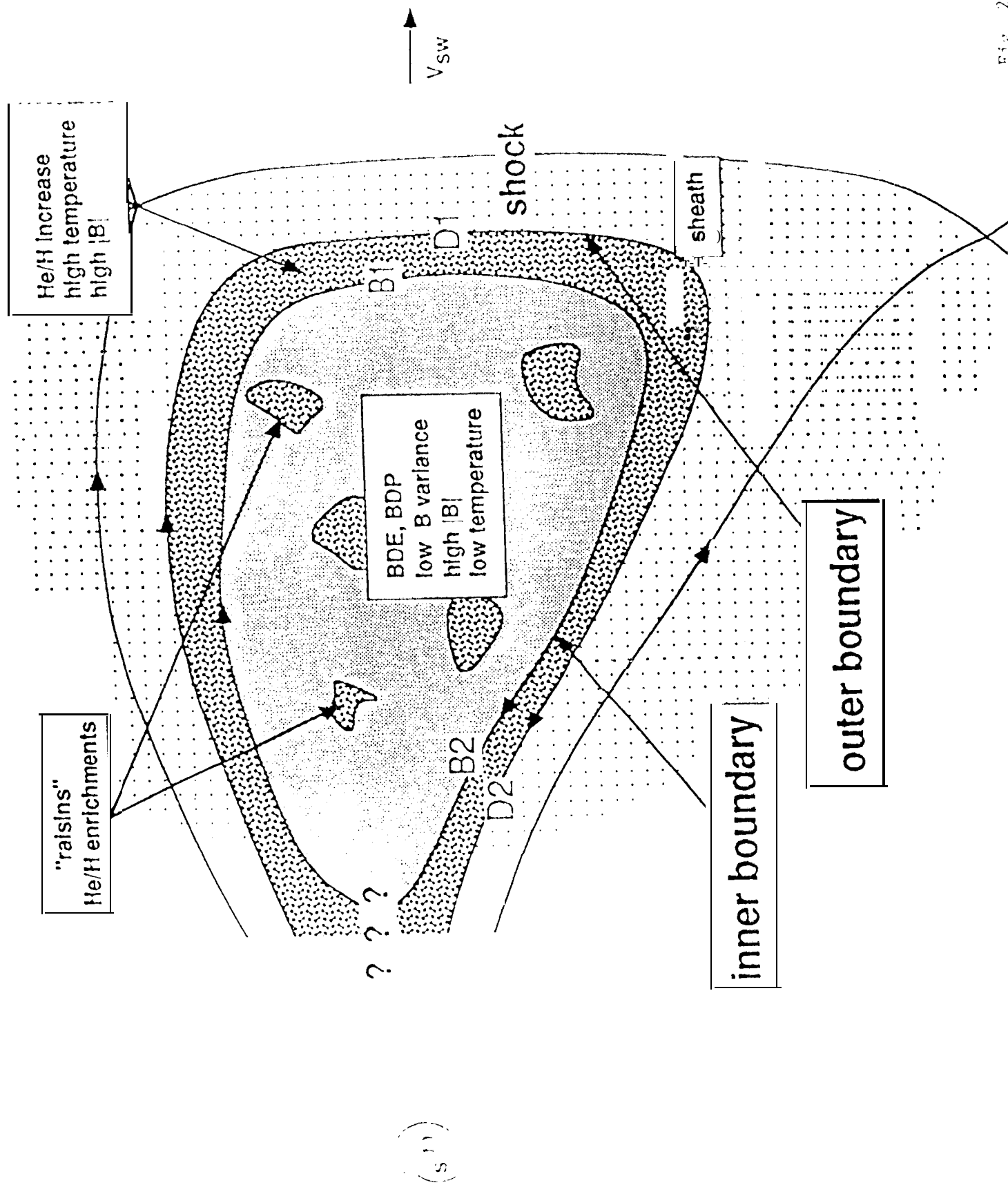
SOLAR WIND'S ELECTRIC FIELD

E: SOLAR WIND'S ELECTRIC FIELD
J: MAGNETOPAUSE CURRENTS
E·J: MAGNETOSPHERIC DYNAMO
X: RECONNECTION REGIONS
①: AURORAL DISSIPATION
②: RING CURRENT DISSIPATION

IMF: INTERPLANETARY MAGNETIC FIELD

-B_z: SOUTHWARD COMPONENT OF IMF
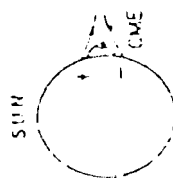
CME: CORONAL MASS EJECTION

Fig 4

Trajectory of trapped particle

Mirror point
(Pitch angle of helical trajectory = 90°)

Magnetic field line

Drift of electrons

Drift of protons

Fig 6

Fig. 7

D_{ST}, nT

SSC

SO

Initial phase

Main phase

Recovery phase

Storm
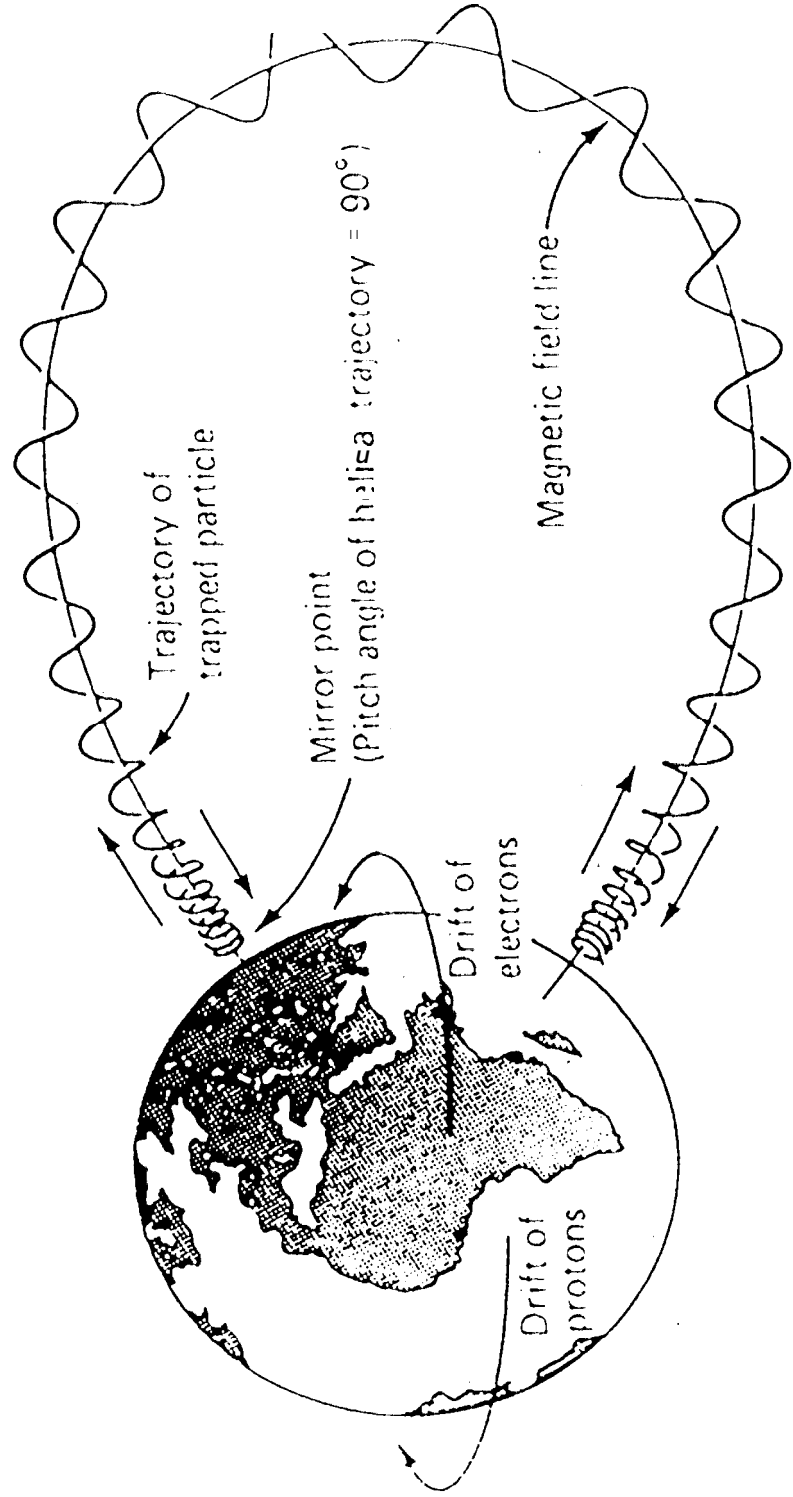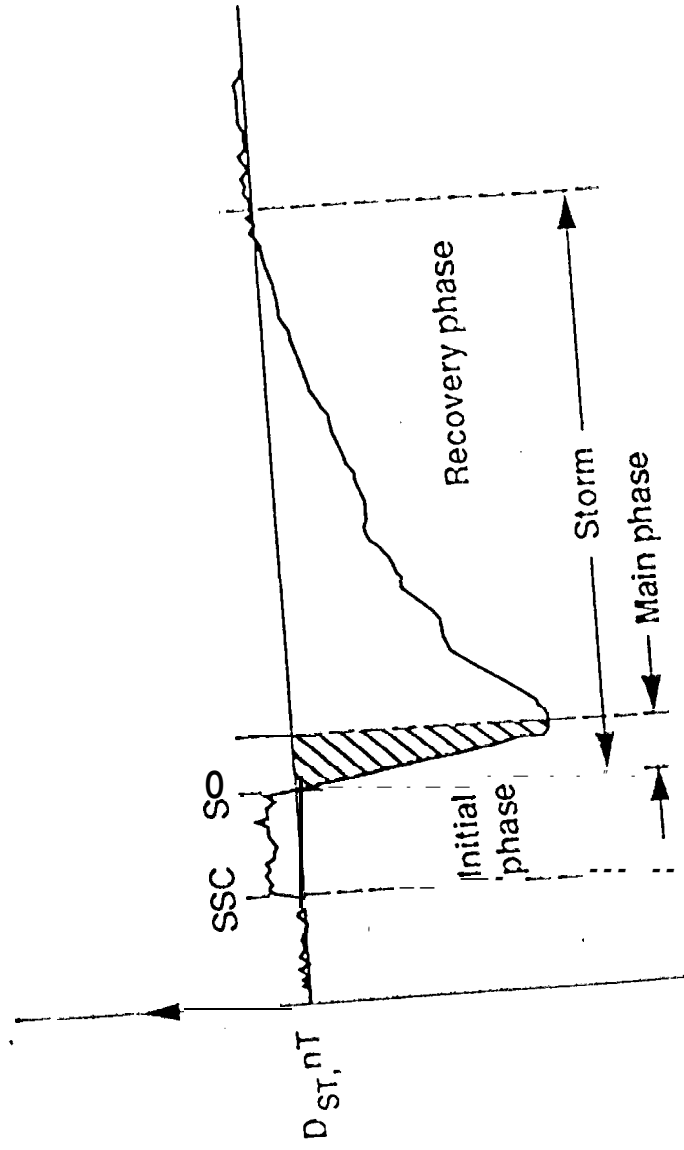
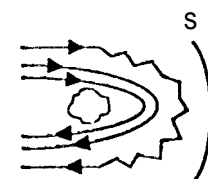# SHEATH FIELDS

a) Shocked southward fields
Tsurutani et. al., 1988
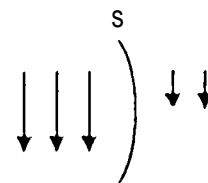
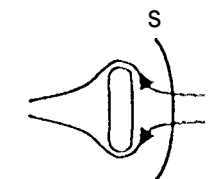b) Shocked heliospheric current sheets
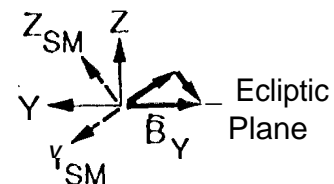Tsurutani et. al., 1984
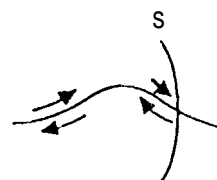
c) 'Turbulence, waves or discontinuities
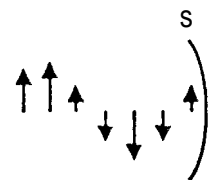
d) Draped magnetic fields
Zwan and Wolf, 1976

e) McComas et. al., 1989
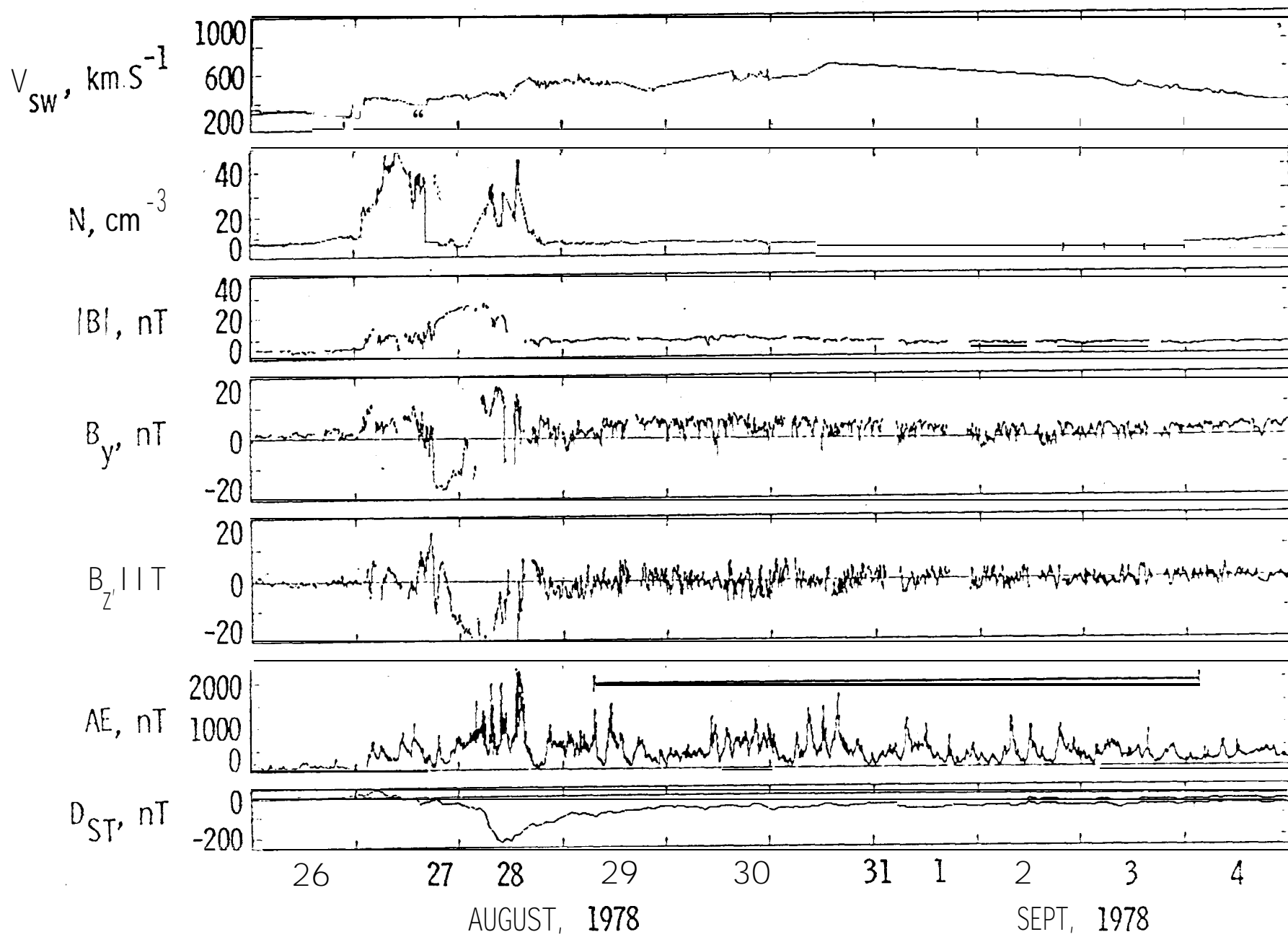
f) Russell and McPherron, 1973;
Crooker et. al., 1992

Fig. 10